Mirror Requirements for Far-IR & Sub-MM

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Executive Summary

Large-aperture lightweight low-cost cryogenic mirrors are an enabling technology for planned NASA far-infrared and sub-millimeter missions such as CMB-Pol, SAFIR and SPECS.

Technical Requirements

- < 10K Temperature – Active or Passive Cooling
- < 10 kg/m2 Areal Density
- > 2 meter diameter Segments for Large Apertures
- < $500K/m2 Areal Cost

JWST Mirror Technology can meet SAFIR requirements but is expensive.

Far-Infrared and Sub-Millimeter Missions

Planned future NASA infrared, far-infrared and sub-millimeter missions:

- Cosmic Microwave Background Polarization (CMB-Pol),
- Single Aperture Far-IR (SAFIR)
- Sub-millimeter Probe of the Evolution of Cosmic Structure (SPECS)
- Terrestrial Planet Finder Interferometer Concept (TPF-I)

need large-aperture lightweight cryogenic optics with similar requirements.

Comparison of Primary Mirror Requirements

Primary Mirror Requirements					
Parameter	JWST	SAFIR	CMB-Pol	SPECS	Units
Primary Diameter	6.5	8 to 12	> 5	15 to 25	meter
Segment Diameter	1.3	1.6 to 2.4	~ 1	> 2	meter
Area	25	50 to 100	20	175 to 500	m^2
Areal Density	25	5 to 10	25	< 5	kg/m^2
Diffraction Limit	2	20	250	20	μm
Surface Figure	0.02	~ 1	~ 10	~ 1	μm rms
Wavelength Range	0.6 to 40	20 to 800	250 to 800	20 to 800	μm
Operating Temperature	<50	~ 4	~ 4	~ 4	K
Cost	\$3 to \$4M	< \$500K	< \$100K	< \$500K	$\$/m^2$
Production Rate	> 0.5	> 2	> 0.5	> 10	m^2/mo
Segment Stiffness	> 200	> 200	> 200	> 200	Hz
Seg Dynamic Survival	> 40	> 40	> 40	> 40	G’s

Mirror Technology

JWST mirrors could be used for SAFIR.

- Optical Performance is Better Than Required
- Beryllium has proven track record at 4K, i.e. Spitzer

But,

- Segments larger than 1.3 meters requires new facility infrastructure
- Cost and Schedule is Prohibitive give SAFIR has 2X to 4X more Area.
- Areal Density is probably a solvable challenge.

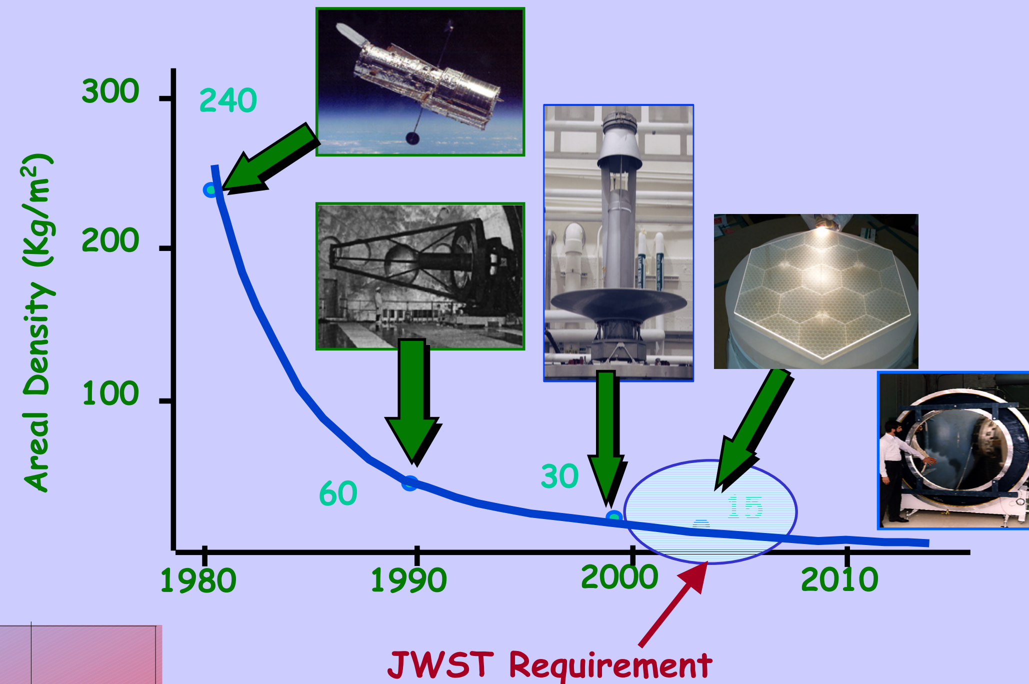
Based on wavelength scaling alone the Areal Cost for:

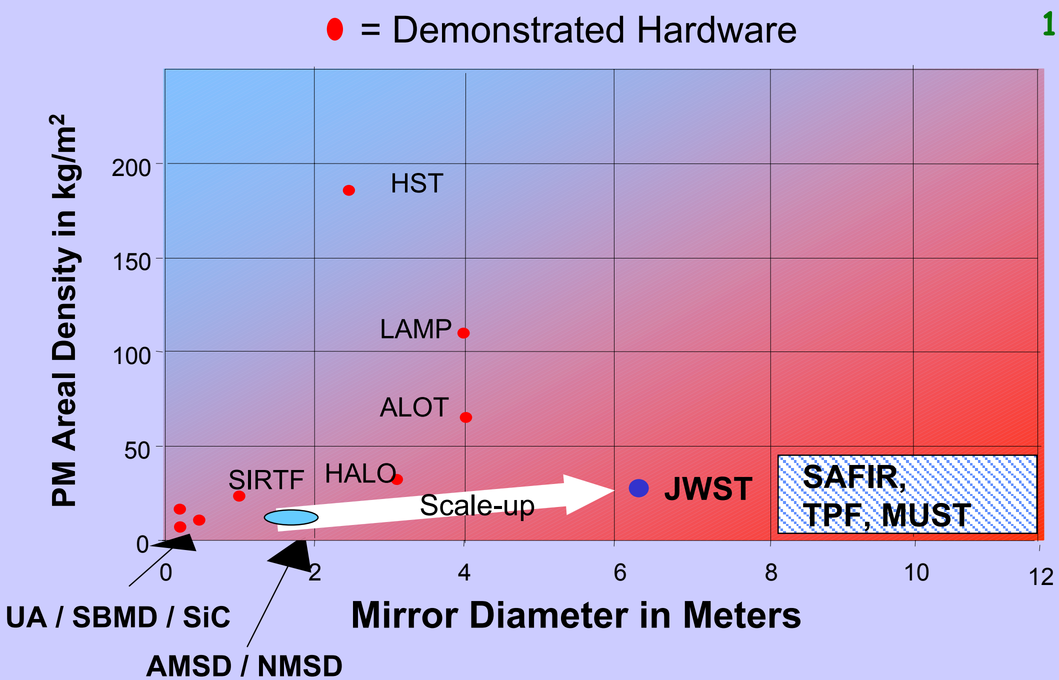
- SAFIR should be 3X less than JWST
- CMB-POL should be 10X less than JWST

But, Goal should be 10X for SAFIR and 50X for CMB-POL.

Mirror Technology Development

- For more than 10 years, the primary goal has been to reduce Areal Density.
- Cost & Schedule is just as important.
- Stiffness is more important.





Primary Mirror	Time	& Cost
HST (2.4 m)	≈ 1 m^2/yr	≈ \$10M/m^2
SIRTF (0.9 m)	≈ 0.3 m^2/yr	≈ \$25M/m^2
AMSD (1.2 m)	≈ 0.7 m^2/yr	≈ \$4M/m^2
JWST (6 m)	> 6 m^2/yr	< \$3M/m^2
SAFIR	> 15 m^2/yr	< \$.5M/m^2

Current Total World Capacity is < 50 m^2/yr

Stable Operation is Critical for Space Telescopes

Lessons Learned from AMSD & JWST

Specific Stiffness is very important:

- Drives Ground Testing via Gravity Sag
- On-Orbit G-Release impacts Error Budgets
- Drives Design for Launch Survival
- Long Term Mechanical Stability

Thermal Stability is other most important parameter:

- Thermal Deformation – Ambient to Cryogenic
- Thermal Gradients – On-Orbit Figure Changes
- CTE, Conductivity, Thermal Capacity, Emissivity

Ideal Material has

- High Stiffness and Low Density – High Specific Stiffness
- High Conductivity and Low CTE – High Thermal Stability

Candidate Materials

Beryllium has been selected for JWST.

- High Specific Stiffness – low density.
- Adequate Thermal Stability

On AMSD, Be experienced a 170 nm rms figure change from Ambient to 30K.

This change is smaller than surface figure error requirement for SAFIR.

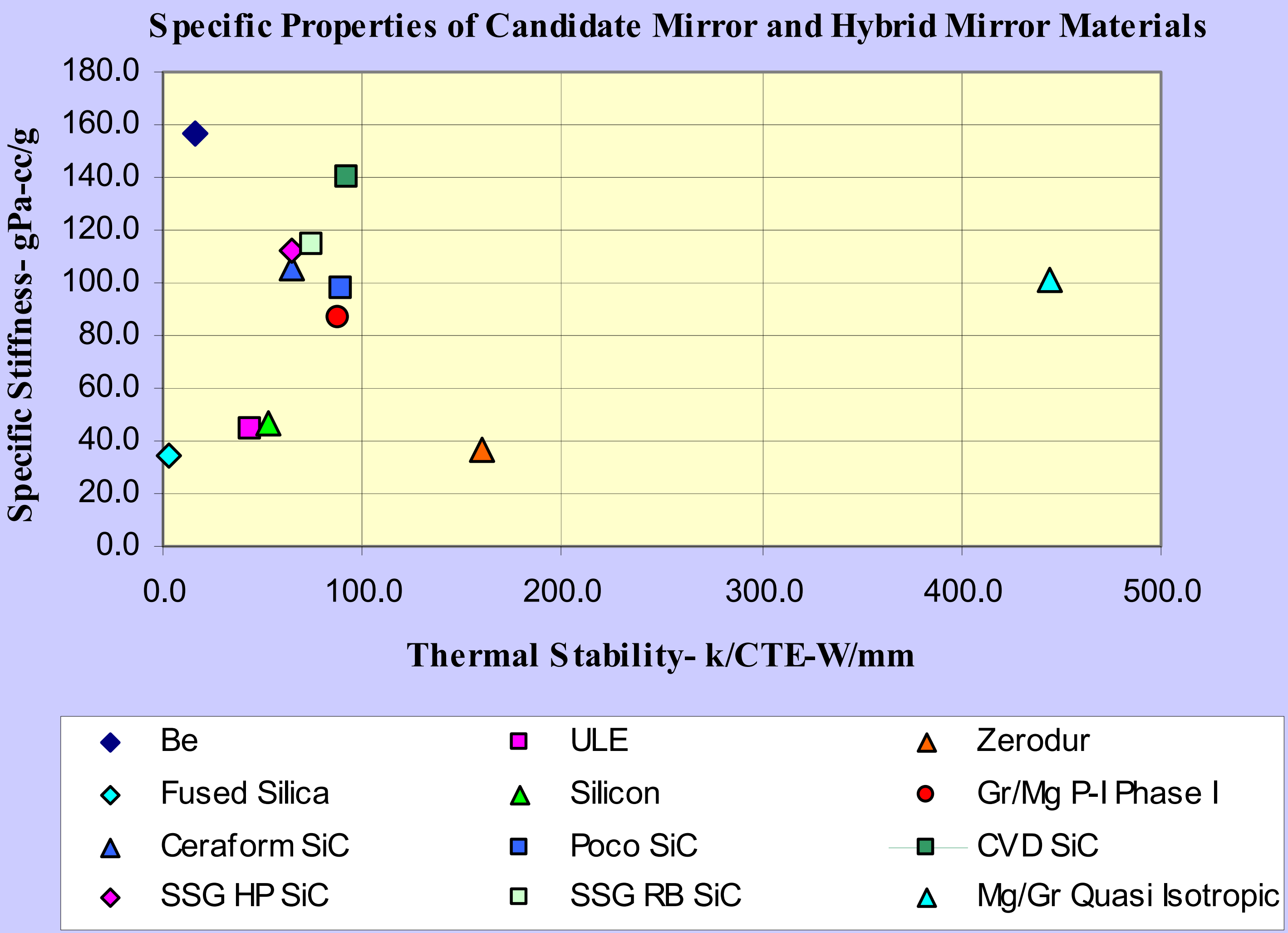
Be could be used on SAFIR without need for Cryo-Null Figuring.

Any material with better Thermal Stability than Be is acceptable.

- Such Materials include SiC, C-SiC, and MgGr (Magnesium Graphite Composite)

Materials (other than Be) with good Specific Stiffness: SiC, C-SiC, MgGr.

Specific Properties of Candidate Mirror Materials
(from MMCC Tech Days 2003)



Design for Stiffness

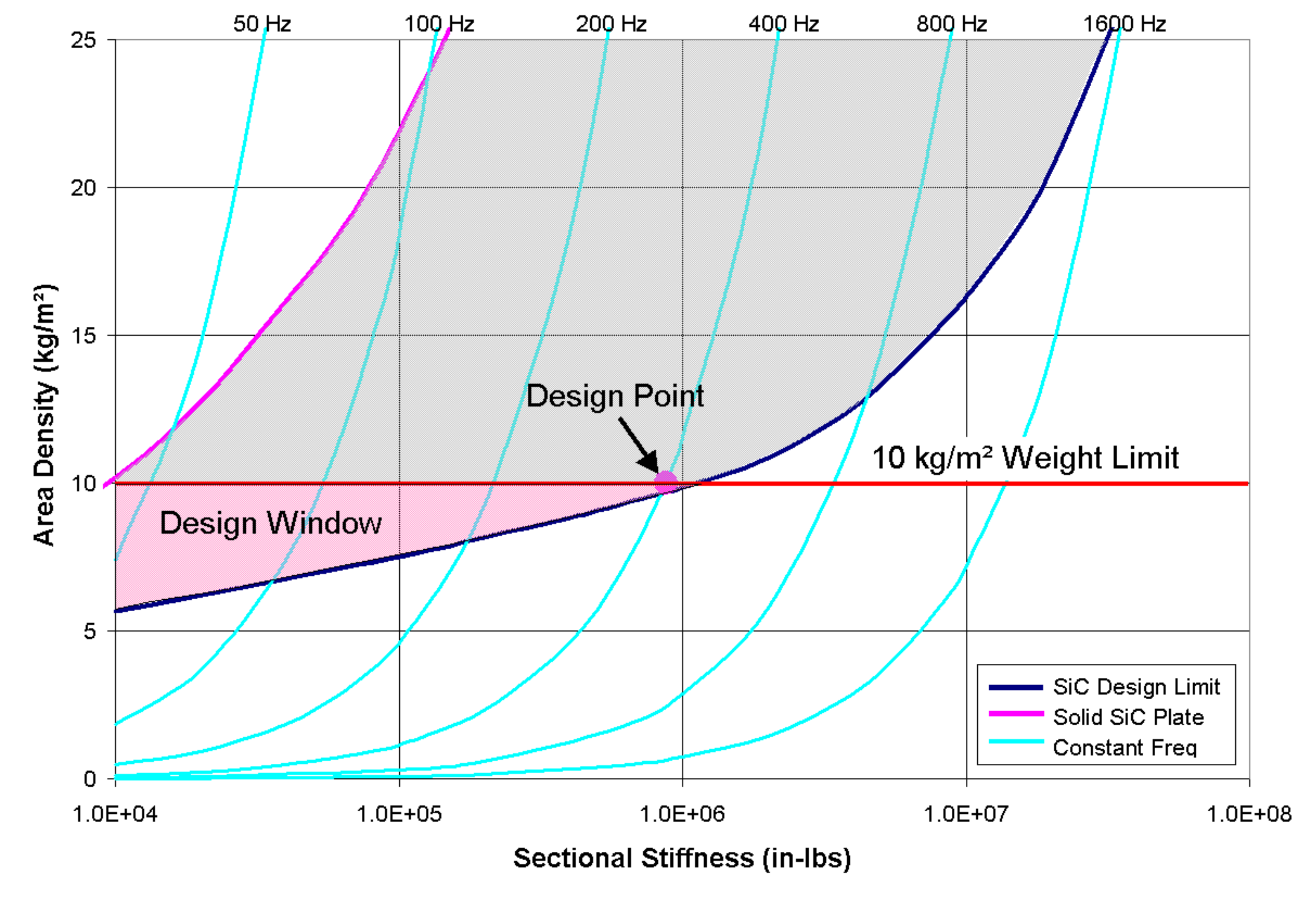
JWST is designing its Be mirrors for > 200 Hz free-free

- Complex trade between:
  - Mirror Depth
  - Face Sheet Thickness
  - Rib Thickness
  - Cell Size
  - Etc.

Xinetics reported on a trade study for SiC Mirrors with >200 Hz free-free stiffness and <10 kg/m2 areal density at Tech Days 2003

Any material with comparable or higher Specific Stiffness to Xinetics SiC should be able to achieve both requirements.

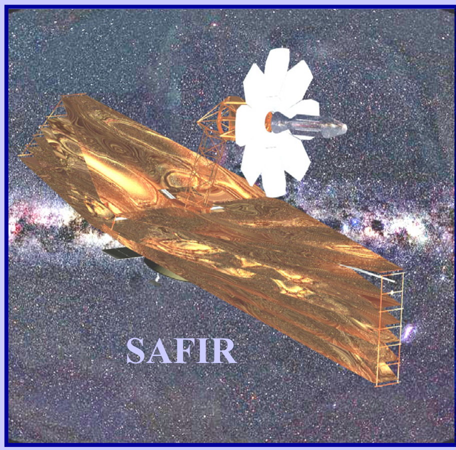
SiC Stiffness to Weight Trade for 1 meter Hex
(from Xinetics Tech Days 2003)

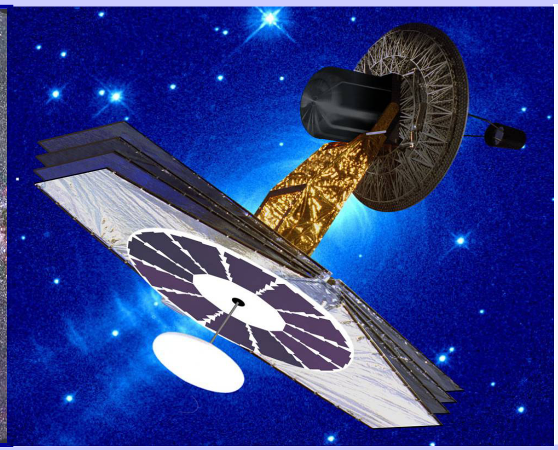


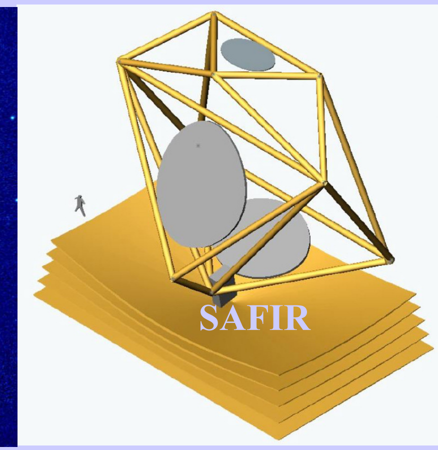
SAFIR

Leading concepts for SAFIR include

deployed segmented architectures similar to JWST and membrane concepts.







JWST class architecture for SAFIR offers:

Demonstrated flight deployment, phasing & pointing to precision greater than required

Re-use of support structure design, mechanisms, actuators, spacecraft, etc.

Mirror Challenges are Cost, Schedule, Stiffness, Mass & Thermal Control.

Cryogenic Mirror Technology Development

The Need for Mirror Technology Development

From its start in 1995, JWST took 8 years to advance lightweight optics for a 30K telescope from TRL-2 to TRL-6 (2003).

Leveraging JWST 30K optics technology, it might be possible to mature SAFIR 4K optics technology to TRL-6 in 6 years if we start today.

SAFIR & SPECS mirror requirements are easier than TPF Interferometer

CMB-POL is on the Technology Roadmap for SAFIR and TPF-I.

Mirror Technology Development requires a Technology Triangle:

- Science Team define science requirements
- Engineering Team matures enabling technology & infrastructure.
- Industry & Universities participate in all phase.

Mirror Technology Development Program

NASA and DoD Partners have invested $40M in mirror technology development projects (via contracts, SBIR's and NRA's):

- AMSD - Advanced Mirror System Demonstrator
  - Ball — Semi-Rigid Low-Authority Be (cryo tested)
  - Kodak — Semi-Rigid Medium-Authority ULE Glass (cryo tested)
  - Goodrich — Iso-Grid High-Authority Fused Silica Glass
- NMSD - NGST Mirror System Demonstrator
  - Arizona — Meniscus Very-High-Authority Glass
  - COI — Rigid Hybrid-Glass-Composite (cryo tested 3 times)
- SBMD - Subscale Beryllium Mirror Demonstrator (cryo tested 7 times)
- Glass Mirrors
  - Hextek — Gas Infusion (cryo tested twice and CNF)
  - Kodak — SiO2 LTF (cryo tested)
  - Schott — Zerodur LTB (cryo tested)
- SiC & C/SiC
  - IABG/ECM — 0.5 meter 7.8 kg/m2 (cryo tested)
  - Xinetics — 0.5 meter 25 kg/m2 (cryo tested)
- Foam Mirrors
  - Schafer — Foam Si (cryo tested)
  - MER and UltraMet Foam SiC
- Other Mirrors
  - JBMD — Joined Beryllium Mirror Demonstrator (cryo tested)
  - MSFC Nickel Replication

AMSD – Ball & Kodak

Specifications

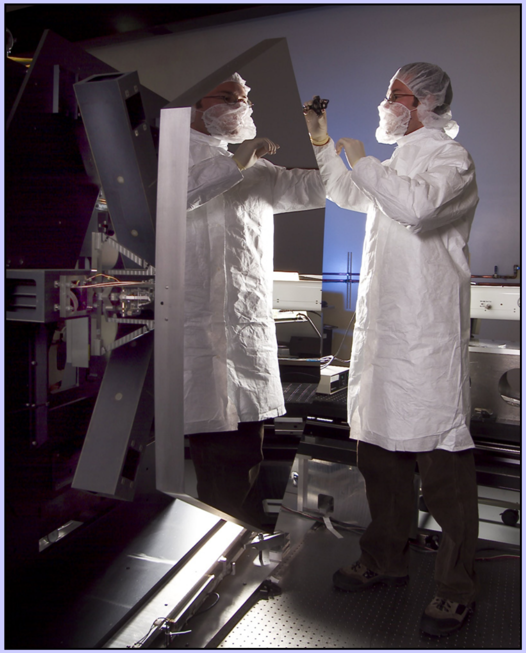
Diameter	1.4 meter point-to-point
Radius	10 meter
Areal Density	< 20 kg/m2
Areal Cost	< $4M/m2

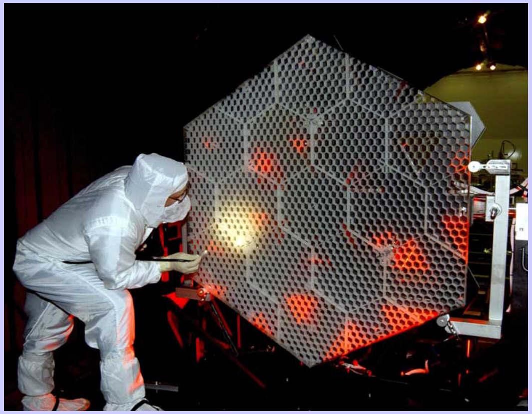
Beryllium Optical Performance

Ambient Fig	47 nm rms (initial)
Ambient Fig	20 nm rms (final)
290K – 30K	77 nm rms
55K – 30K	7 nm rms

ULE Optical Performance

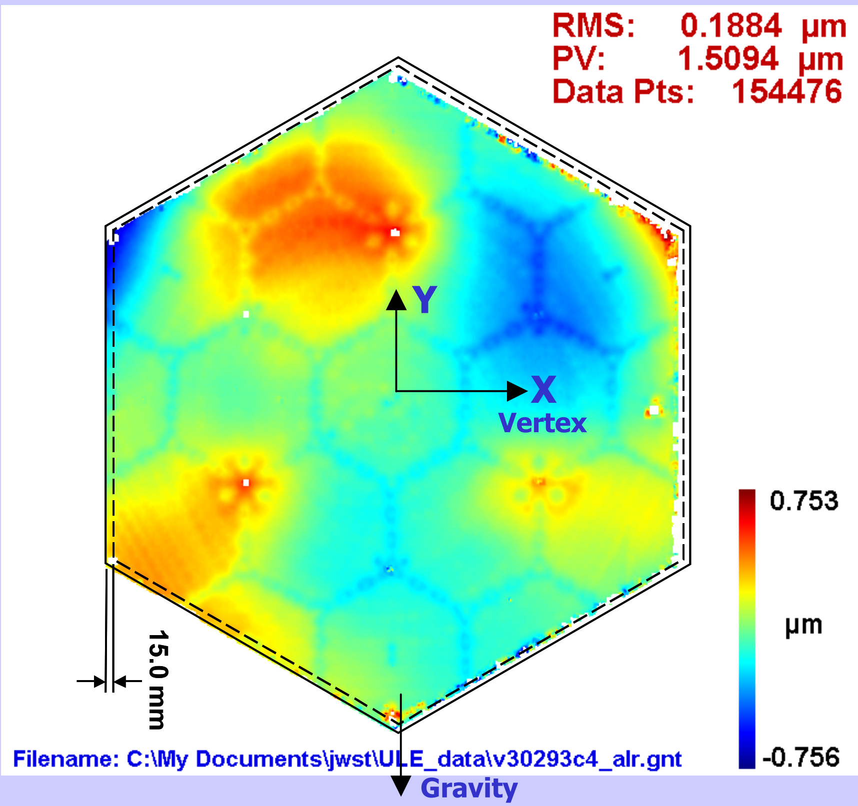
Ambient Fig	38 nm rms (initial)
290K – 30K	392 nm rms
55K – 30K	55 nm rms
290K – 30K	188 nm rms (w/ adjust)
55K – 30K	20 nm rms (w/ adjust)



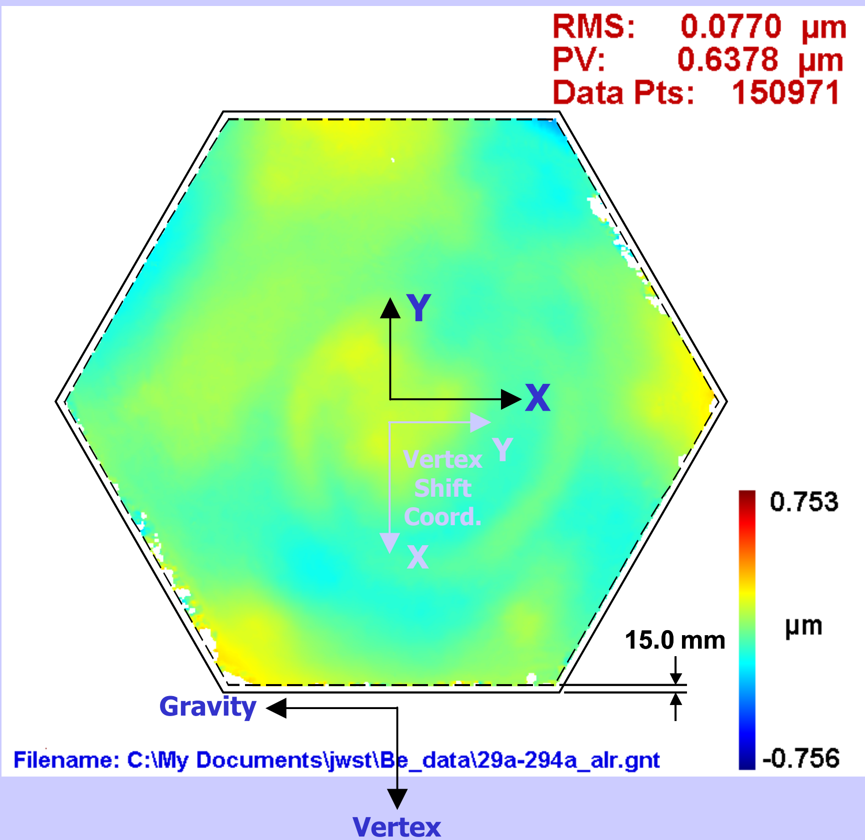


Static Cryogenic Figure Change

~30 K minus Ambient with Virtual Hexapod Alignment Adjustment



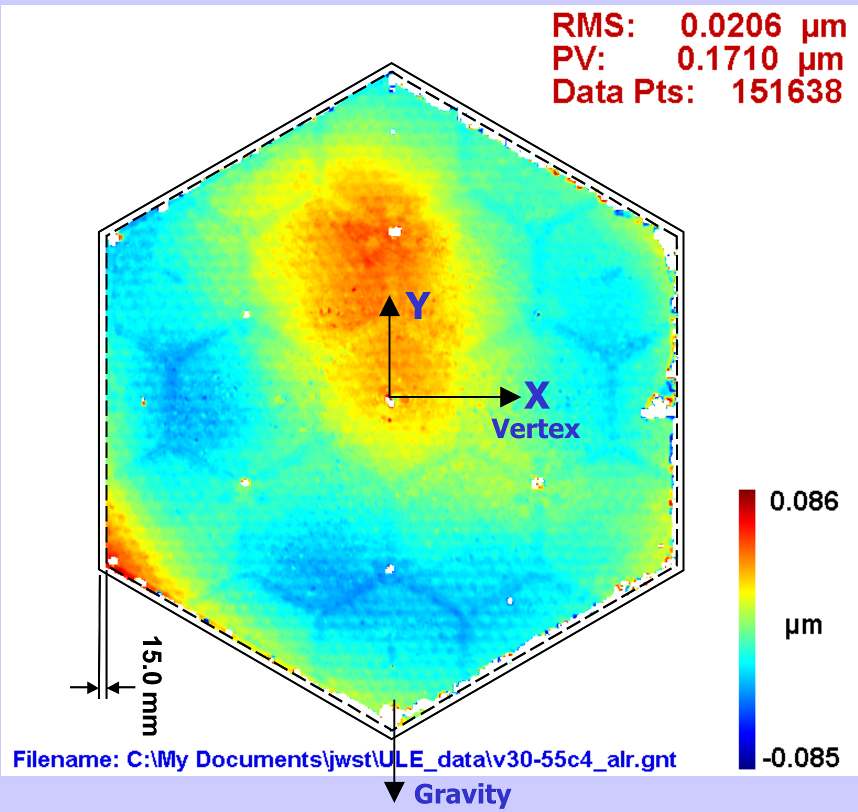
Kodak ULE



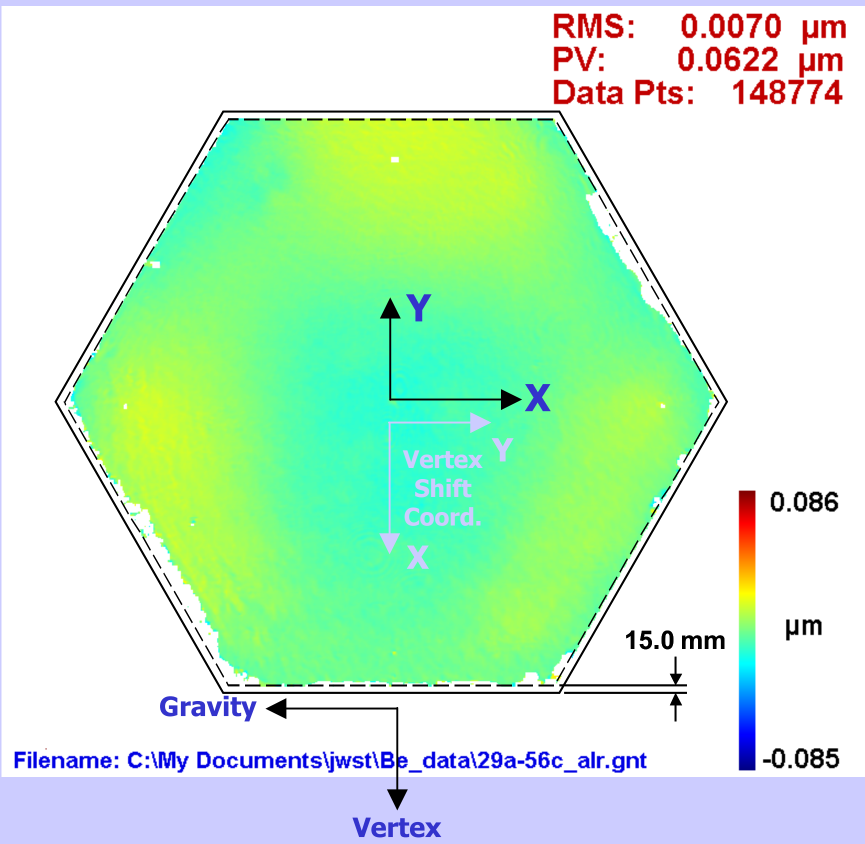
Ball Be

Operational Range Thermal Stability

~30 K minus ~55 K with Virtual Hexapod Alignment Adjustment



Kodak ULE



Ball Be

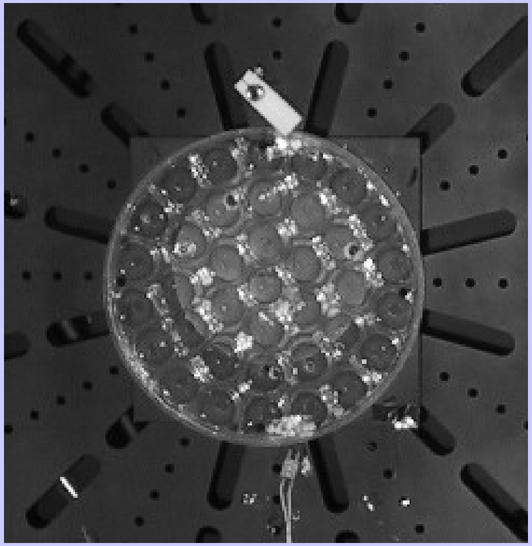
Hextek Gas Infusion Mirror

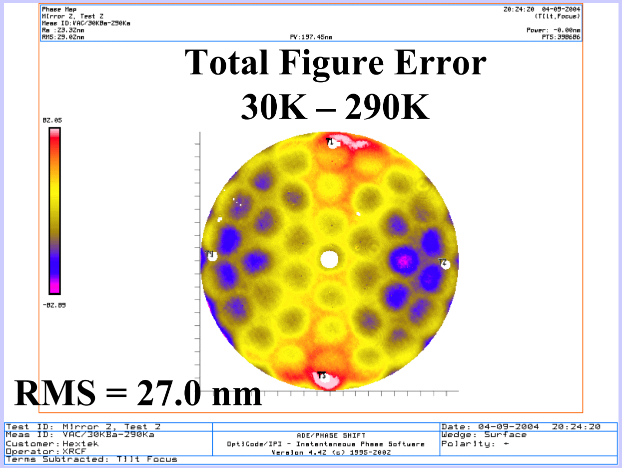
Specifications

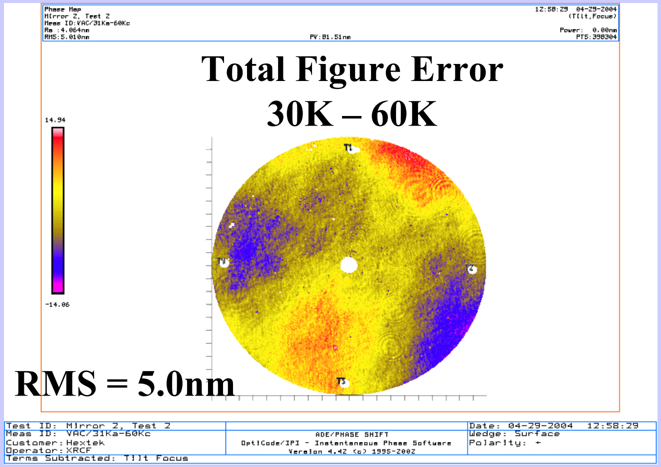
Diameter	0.25 meter
Radius	2.5 meter
Areal Density	< 10 kg/m2
Areal Cost	< $300K/m2

Polished by MSFC

Ambient Fig	23 nm rms
30K Figure	40 nm rms
30K – 290K	27 nm rms
30K – 60K	< 5 nm rms







Cryo Null Figured by QED with Residual Error of 13 nm rms

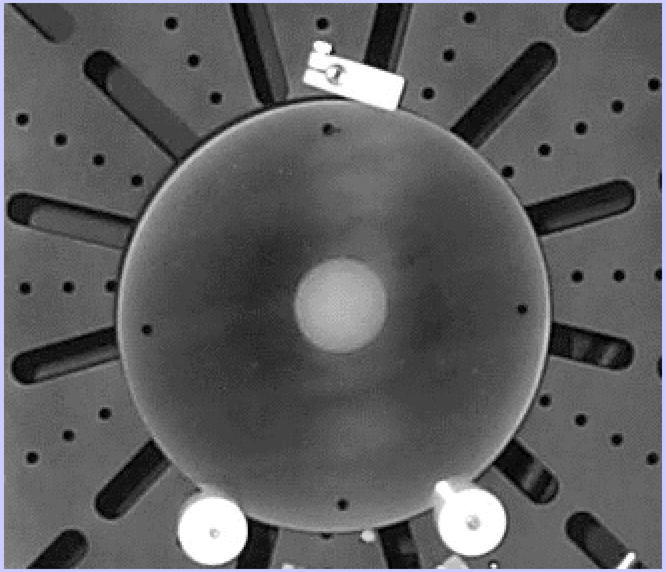
POCO SiC Mirror

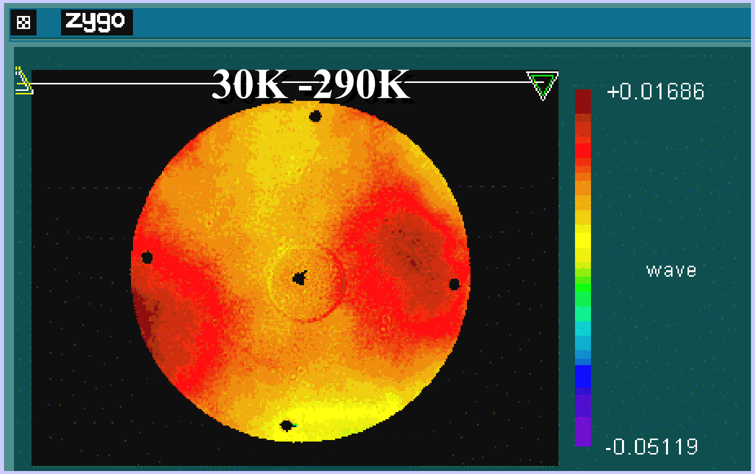
Specifications

Diameter	0.25 meter
Radius	2.5 meter
Areal Density	< 10 kg/m2
Areal Cost	< $1M/m2

Delivered Polished

Ambient Fig	89 nm rms
30K Figure	96 nm rms
290K – 30K	16 nm rms





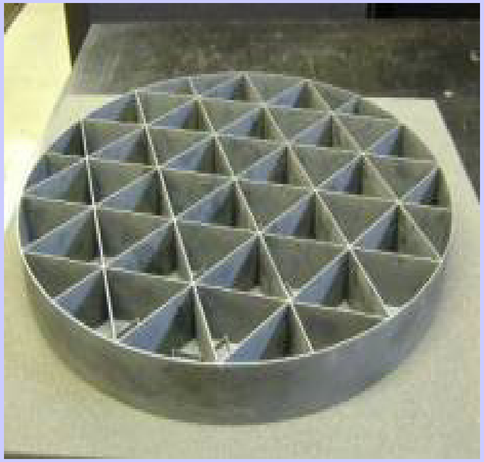
Xinetics SiC Mirror

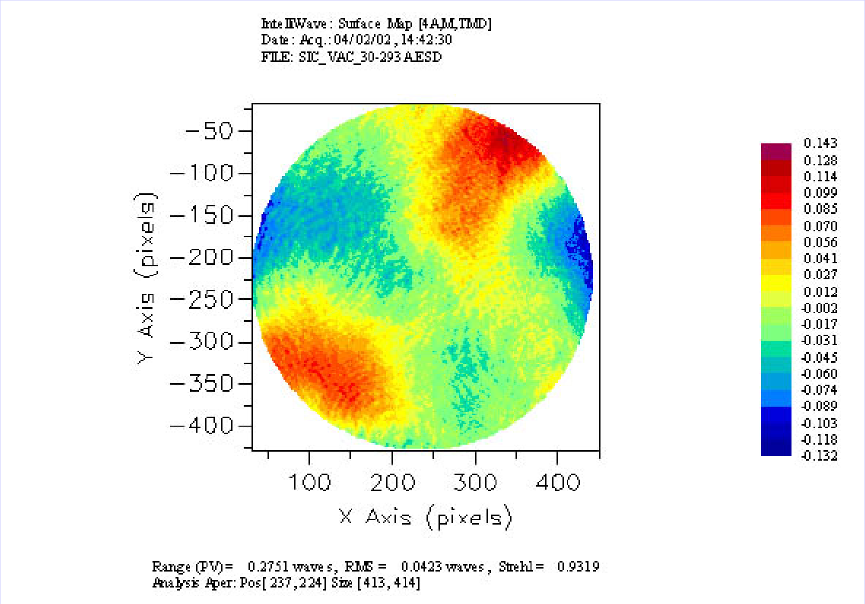
Specifications

Diameter	0.5 meter
Radius	20 meter
Areal Density	< 20 kg/m2
Areal Cost	< $1.5M/m2

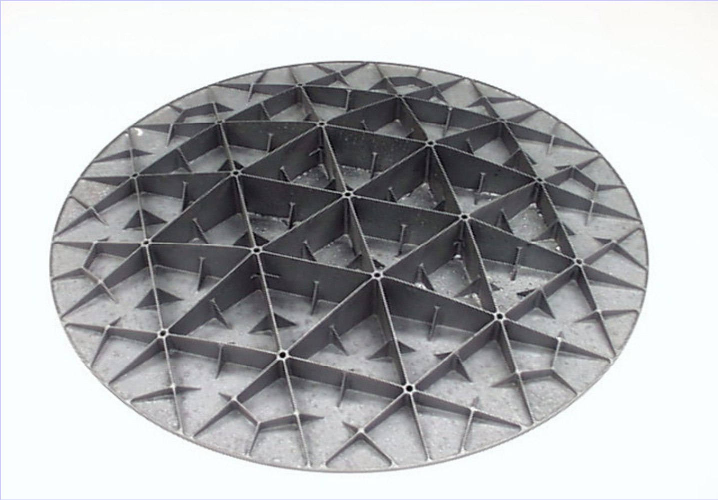
Delivered Polished

Ambient Fig	300 nm rms
290K – 30K	27 nm rms





IABG 0.5 m 20 m Rcv Carbon Silicon Carbide



IABG Carbon Silicon Carbide Mirror C/SiC

0.5 m Diameter
20 m Rcv
7.8 kg/m^2 Areal density

Blank polished at General Optics

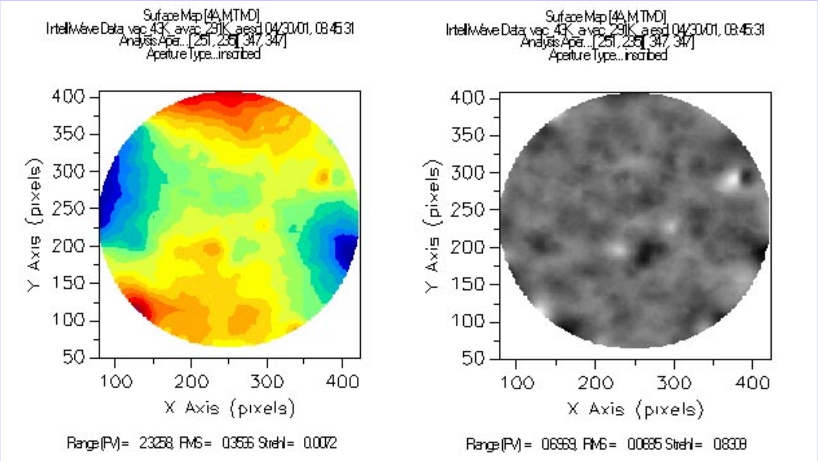
Figure of ½ wave PV
Finish of 100 Angstroms RMS

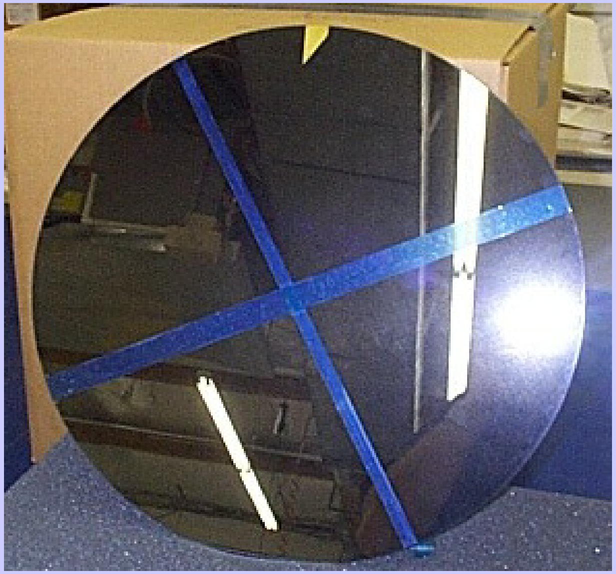
Mirror tested to 120K at Kodak (Sept 99)

280 nm RMS, 2.53 µm PV Cryo-Figure Change

Mirror tested to 30K at MSFC (Apr 01).

350 nm RMS, 2.32 µm PV Cryo-Figure Change





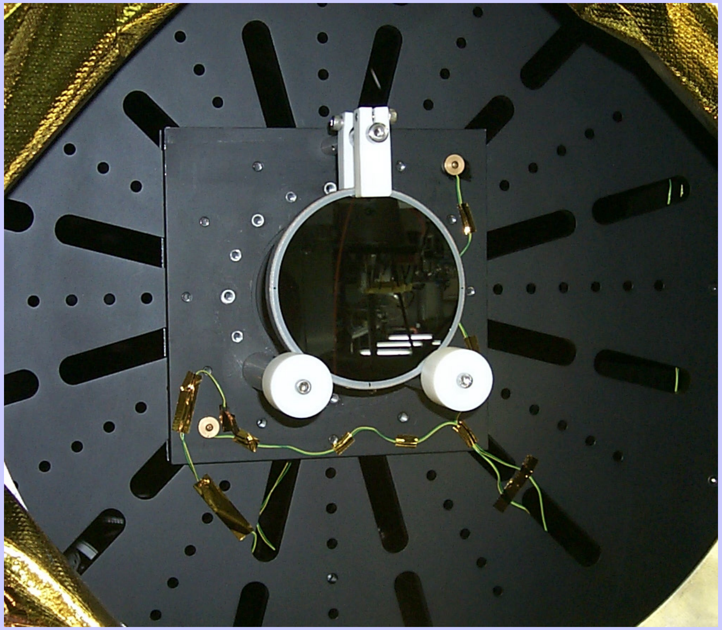
Schafer SLIM (Si Foam) Mirror

Specifications

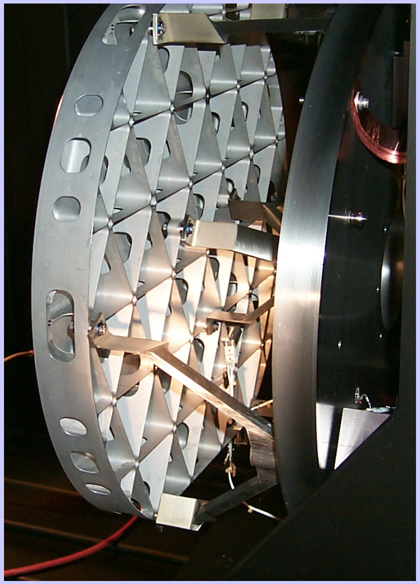
Diameter	0.125 meter
Radius	0.6 meter
Areal Density	< 10 kg/m2
Areal Cost	< $2.5M/m2

Delivered Polished

Ambient Fig	29 nm rms (free)
290K – 30K	10 nm rms (free)
290K – 30K	46 nm rms (mounted)
75K – 30K	< 4 nm rms (free)



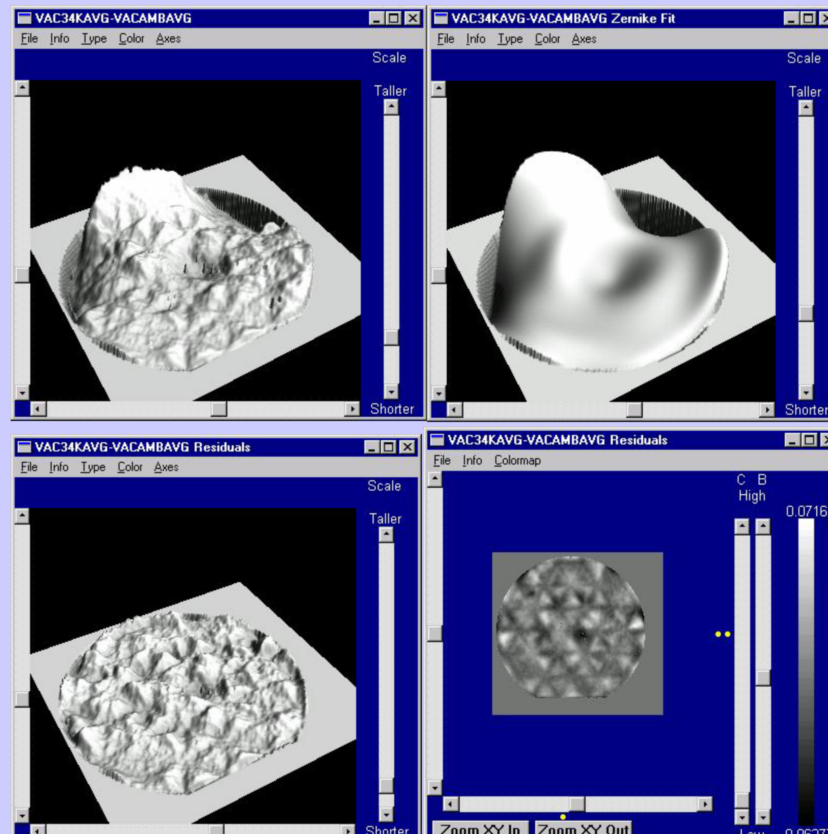
Ball Subscale Beryllium Mirror Demonstrator (SBMD)



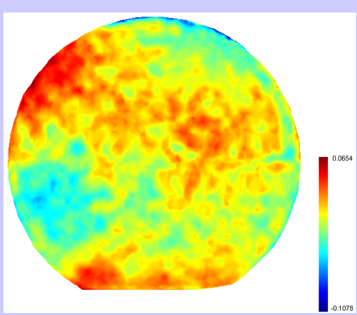
Cryogenic Surface Error (34K -288K)

Total (0.571 µm p-v; 0.063µm rms)

Low Order (0.542 µm p-v, 0.062 µm rms)



0.5 m diameter, 20 m ROC, 9.8 kg/m^2 areal density, O-30 Beryllium Mirror



Cryo Tested at MSFC

Higher Order Residual (0.134 µm p-v; 0.012 µm rms)

COI Hybrid Mirror

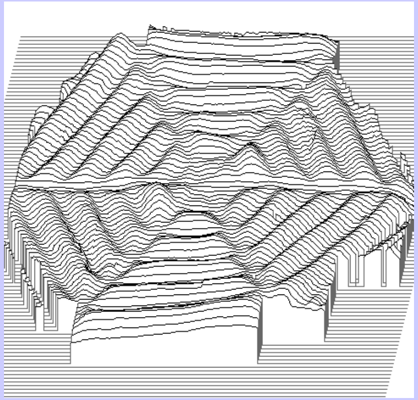
Specifications

Diameter	1.6 meter
Radius	20 meter
Areal Density	< 15 kg/m2
Areal Cost	< $2.5M/m2

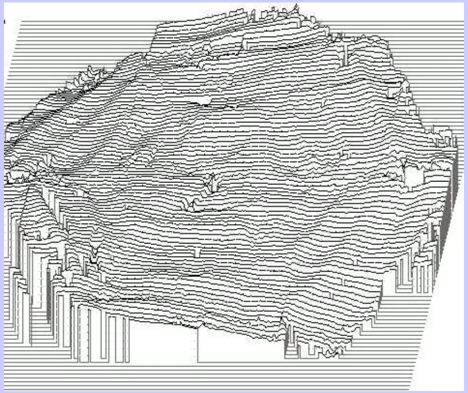
Delivered Polished with Cryo-Null Figure

25K Figure	800 nm rms

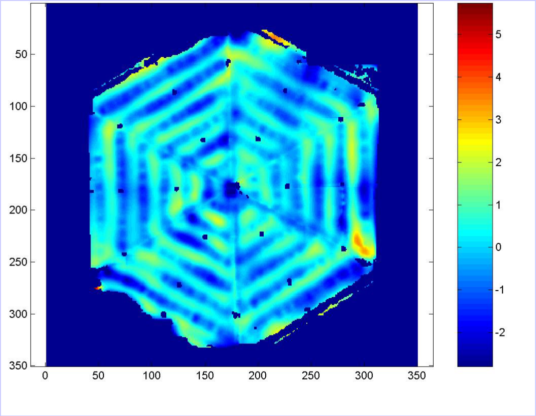
25K Figure
(Low Order Zernikes Removed)



Ambient Surface



Surface at Cryo

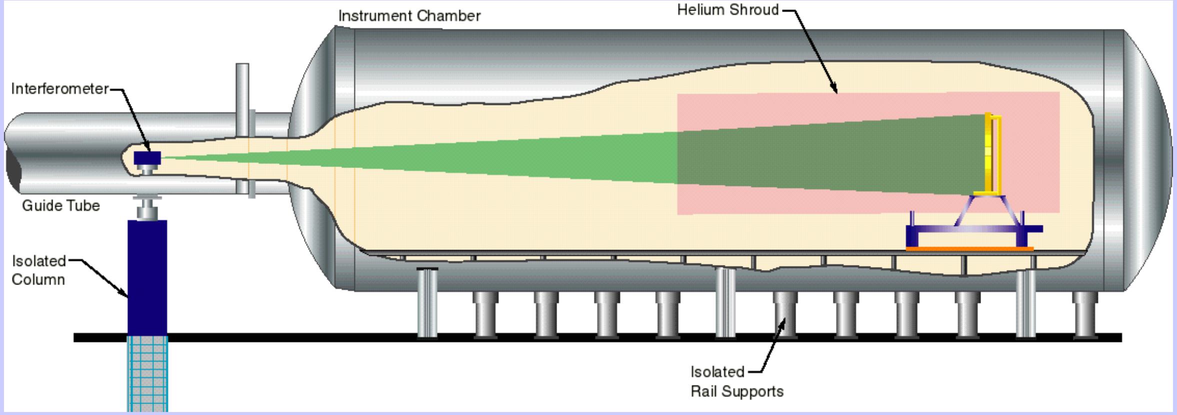


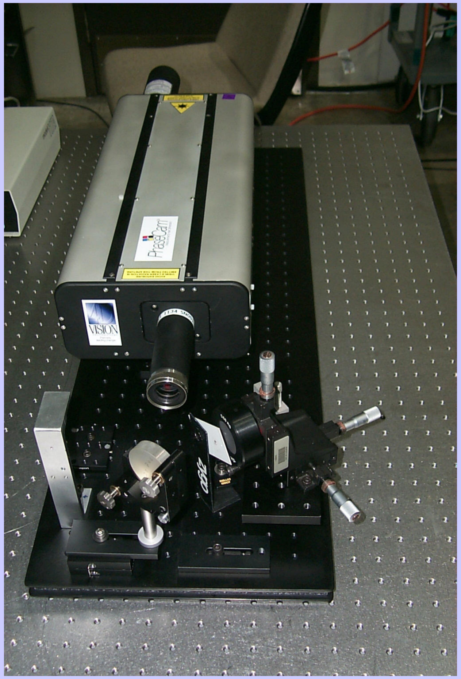
0.8micron RMS Full Aperture
0.48micron RMS Masking Gravity Offload influences

Ability to Cryo-Test JWST Segments is TRL 6

Cryogenic Testing at MSFC is Routine

Performed 10+ Tests to 30K , Reduced Test Times from 7 to 5 to 3 weeks





Invested in Special Test Equipment and Procedures

PhaseCAM Instantaneous Interferometer

Stroboscopic Modal Test Interferometry

Leica Absolute Distance Meter (ADM)

100X Accuracy/Resolution Improvement

Segment Radius of Curvature Matching

NASA Space Optics Manufacturing Technology Center (SOMTC)

Executive Summary

Space Optics is a core technology at MSFC

MSFC's world-class optics personnel & facilities enable:

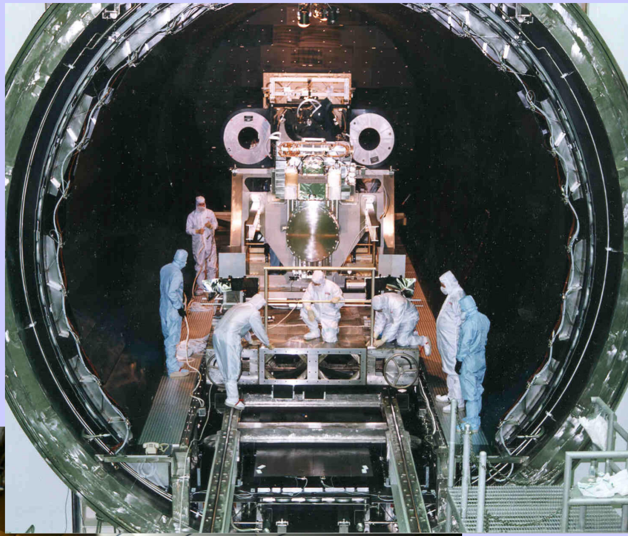
- James Webb Space Telescope (JWST)
- Constellation X (ConX).
- Extreme Universe Space Observatory (EUSO)

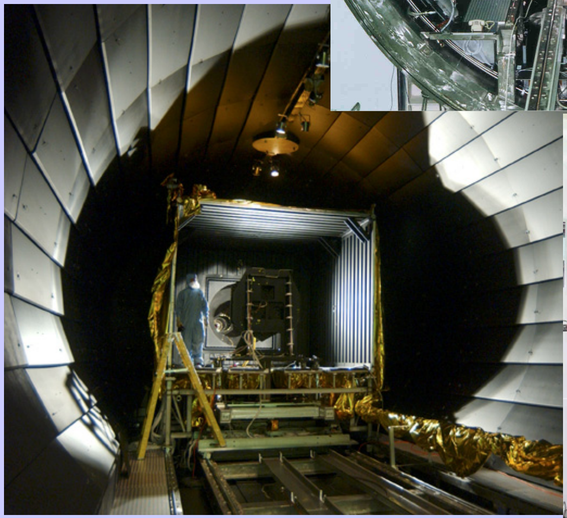
MSFC Optics Group is committed to supporting future Code S missions:

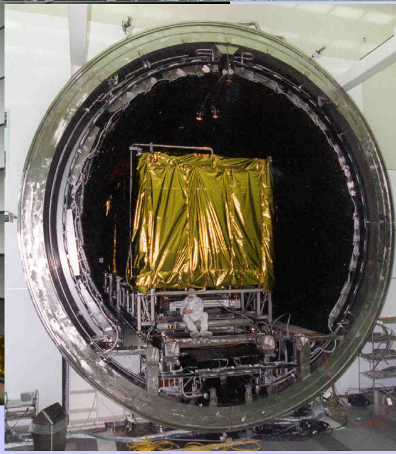
- Single Aperture Far Infrared (SAFIR),
- Terrestrial Planet Finder (TPF),
- Modern Universe Space Telescope (MUST).

Cryo Mirror Technology Development:

- AMSD, NMSD & SBMD
- Funded SBIR Contracts
- MSFC IRAD Investments
- Submitted Large Cryo Mirror NRA



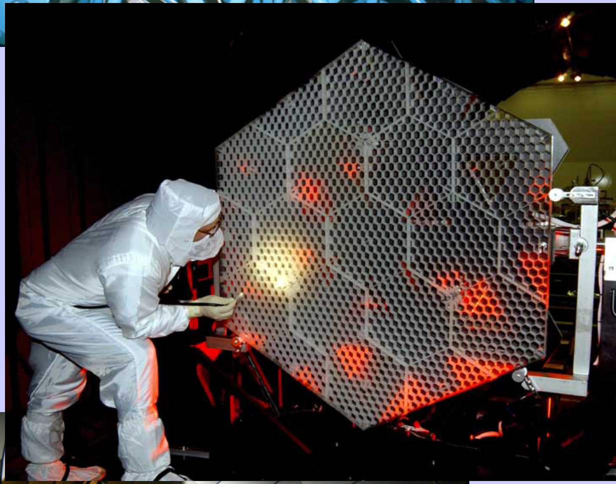




Proven Record in Large Optics

Recognized experts in optical fabrication & testing

- Worked on most of world's largest monolithic & segmented telescopes: SUBARU, KECK, HET, LAMP, AMOS, Starfire, VLT, Gemini, etc.
- Ultra-Precision Metrology – LIGO, Lithography, etc.



Unsurpassed experience in cryogenic & x-ray performance testing

- Over 40 cryogenic tests of large optics, structures and mechanisms since 1999.
- Over 12 X-ray performance tests since 1999 (plus HEAO-B, SXI & Chandra < '99)

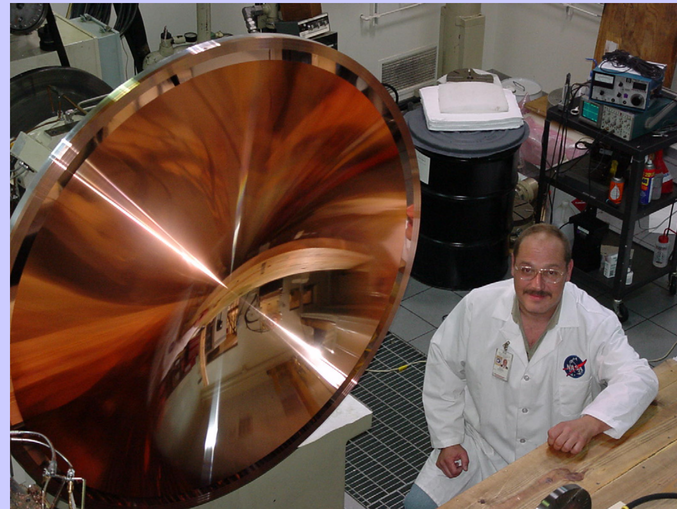
Unique world class test facilities & instruments

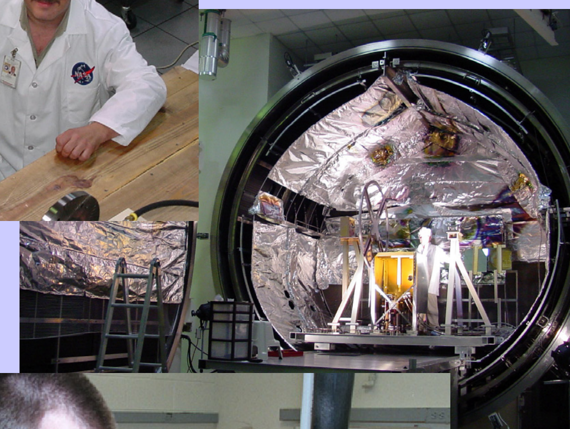
- XRCF, Straylight, Metrology

MSFC Optics Core Capabilities Compliment those of GSFC & JPL

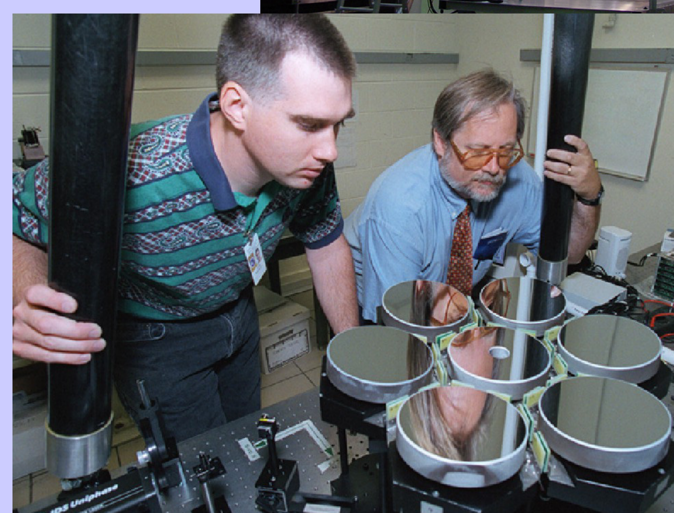
Fabrication and Test of:

- Large Space Optics
- Cryogenic Optics
- Transmissive and Fresnel Optics
- X-Ray Optics
- Replicated and Gossamer Optics.





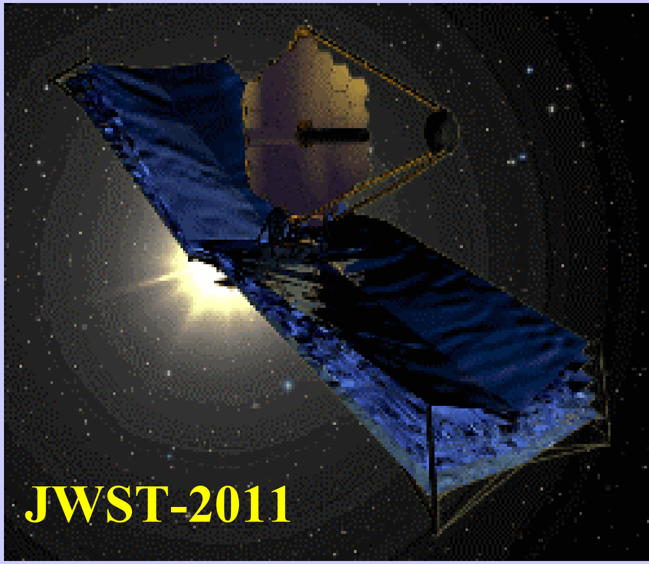
Laser Technology Development
Diffractive Optics and Photonic Sensors
Coating Technology Development
Material Research
Segmented Telescope Alignment
Space Power
Optical Propulsion and Solar Sails
Optical Diagnostics for Microgravity Research
Optical Diagnostics for Propulsion Research
Optical Education and Public Outreach



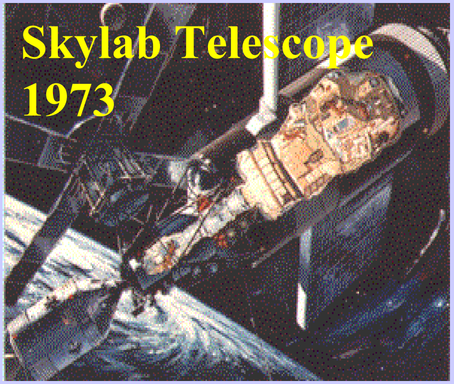
MSFC Optics Support Code S Missions

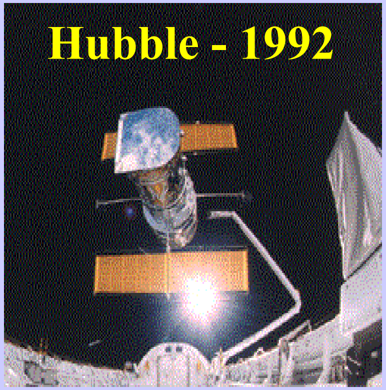
Current Programs:

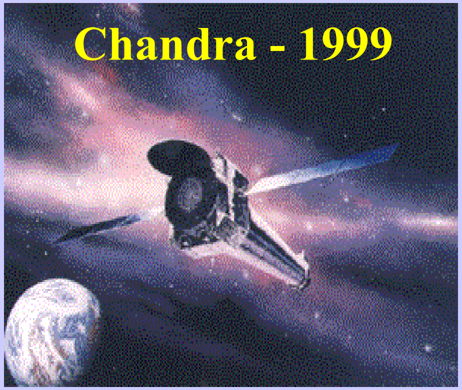
- James Webb Space Telescope (JWST) - GSFC
  - Optical Components Lead – Insight/Oversight
  - Cryogenic Testing of Flight Mirror Segments
- Constellation X (ConX) – GSFC
  - Support Optics Fab & Metrology, X-Ray Testing
- Solar X-Ray Imager (SXI) - GSFC
- Solar B - MSFC
- Gravity Probe B - MSFC
- SUMI - MSFC
- Extreme Universe Space Observatory (EUSO) - MSFC
- Terrestrial Planet Finder (TPF) – JPL/GSFC
- Space Interferometer Mission (SIM) – JPL



MSFC has significant Flight Heritage







MSFC's Record on JWST

Pre-Phase A Activities

- Significant contributions to NGST Strawman Concept
- Performed L2 Environment study for JWST.

Mirror Technology Development Lead

- Managed SBMD, NMSD & AMSD Programs
- Cryogenic Performance Testing of SBMD, NMSD, AMSD, etc.
- Created new commercial tools – 4D PhaseCAM, Leica ADM, SRS IODA
- Material Property Testing
- Integrated Modeling
- Risk Planning

Procurement Support

- Voting Member on Source Evaluation Board
- Voting Member on Primary Mirror Material Selection Board
- Lead OTE Cost Modeling

Flight Program

- Key members of the OTE Management Team
  - Optical Components: primary, secondary & tertiary mirrors
- Primary Mirror Segment Testing at MSFC - FY05 to FY07/08
  - Ambient Verification – prevents prescription error.
  - Cryogenic Characterization – enables on-orbit performance.

X-Ray and Cryogenic Test Facility

Facility

- 7 x 23 m Stainless 10-8 Torr Chamber
- Vibration Isolated (LOS Jitter 5 - 10 urad)
- 5DOF Remote Controlled Test Stand

Personnel

- Experience Team provides 24/7 support
- 35+ Cryogenic Mirror & Structure Tests
- 12+ X-Ray tests

Cryogenic Testing

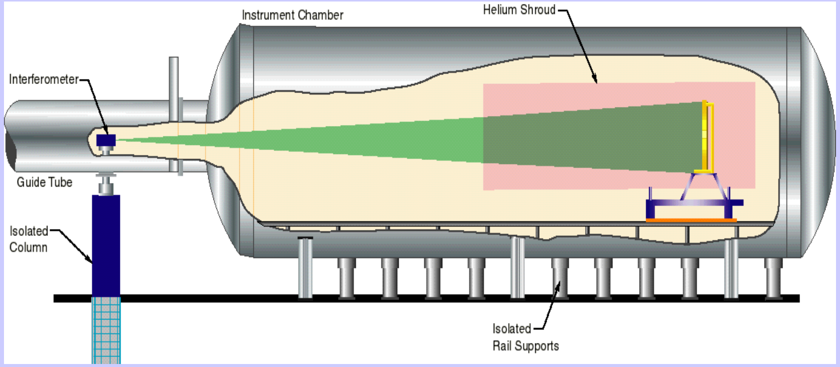
- 6 x 18 m LN2 Shroud with Heaters for 166K to 344K Thermal Range
- 2.7 x 3.3 x 10 m 20K Closed Loop He Shroud (design for 4.4 x 3.9 x 18 m)

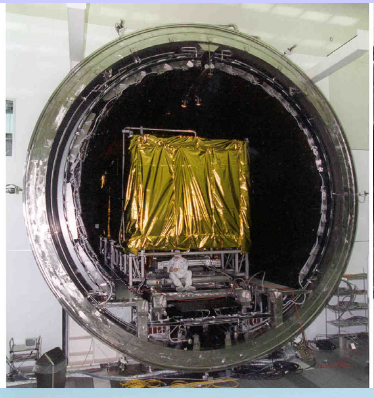
X-Ray Testing

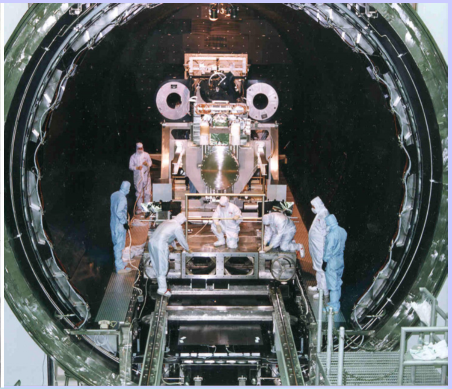
- Full aperture testing up to 1.46 m
- Collimation via 0.518 km evacuated tube.
- Instrumentation (0.1 to 10.0 KEV).

Telescopes/Components Tested

- Einstein, Chandra, SXI, HEAO, CXM
- SBMD, NMSD, AMSD, JWST
- Continuous Usage since 1999; 47% Vacuum
- Projected Usage for JWST and ConX







XRCF is a Unique World Class Facility

No other facility has the XRCF's combination of size, stability, cleanliness, cryogenic optical test and x-ray test capabilities.

Large Thermal Vacuum Chambers								
Chamber	Size [m] Dia x Len	Orient	Temperature				Clean [class]	Stable
			20K	77K	>77K	Thermal		
MSFC XRCF	7.3 x 22.8	Horz	X	X	X	340K	100	< μg
GSFC SES	8.2 x 12.2	Vert	X	X	X	370K	10K	< μg
Glenn SPF	30 x 35	Vert		X	X		100K	< μg
AEDC Mark 1	12.8 x 25	Vert		X	X	370K	1K	> mg
AEDC 10V	3 x 9	Horz	X				100	< μg

X-Ray Test Facilities			
Chamber	Dia x Len [m]	Max Beam Dia [m]	Source @ [m]
MSFC XRCF	7.3 x 22.8	1.46 m	518
MSFC Straylight	3 x 12	1.0 m	101
German Panther	3.5 x 12		130